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16. Abstract

This report describes activities in ATC Surveillance/Communication Analysis and Planning funded by the Federal Aviation Administration. It is the first Quarterly Technical Summary of this program, covering the period 1 September to 1 December 1971. The activities include preparation of a final "Technical Development Plan for a Discrete Address Beacon System" in cooperation with FAA personnel and initiation of planning activities in preparation for undertaking the system engineering responsibility on DABS. Other activities initiated during the reporting period include air traffic surveillance requirements studies, investigations of current system performance, and investigations of critical areas related to the design of DABS. Field measurement of ATCRBS transponder performance has continued during the reporting period.

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CONTENTS

ATC SURVEILLANCE/COMMUNICATION ANALYSIS AND PLANNING

I. INTRODUCTION

This is the first Quarterly Technical Summary, covering the period 1 September to 1 December 1971, of the work performed by Lincoln Laboratory under Interagency Agreement DOT-FA72WAI-242 between the Federal Aviation Administration and the United States Air Force. The Statement of Work includes four tasks to be carried out under this Interagency Agreement; these are summarized as follows.

1. Determine the air traffic surveillance and air/ground data-link communication capability required to support the air traffic control system for the forthcoming 15-year period.
2. Perform trade-off studies of alternative approaches to meeting the requirements outlined in Task 1. The approaches considered should include systems utilizing combinations of upgraded ATCRBS, a Discrete Address Beacon System (DABS), primary radar, and VHF data link. System comparisons should take into account the possible availability of an (undefined) "Fourth Generation" system in the 1990 time frame.
3. Undertake detailed investigations of critical areas involved in the design of DABS.
4. Provide technical support as required to the FAA Communication Development Division.

At the time when this effort was begun, Lincoln Laboratory was preparing for the FAA, under a separate Interagency Agreement, a "Draft Technical Development Plan for a Discrete Address Beacon System."[1] Task 3 was intended to provide an early start on resolving the critical issues related to the design of DABS, with the recognition that these efforts would become part of an over-all DABS development program as soon as one was initiated. During the latter part of this reporting period, the FAA asked Lincoln Laboratory to undertake, under a separate Interagency Agreement, the system engineering of DABS. It is anticipated that this effort will commence on or about 3 January 1972. Subsequent work on the efforts defined under Task 3 will be supported by, and reported as part of, the DABS System Engineering effort. The requirements analysis called for in the final Technical Development Plan for DABS[2] will be performed under an expanded Task 1 and reported as part of this effort. Further, the dropping of Task 3 will permit greater depth in the consideration of alternative approaches (Task 2) and will make additional support available in related areas under Task 4.

Specific efforts undertaken during this reporting period include the following:

1. In cooperation with FAA personnel from the Communication Development Division and Office of Systems Engineering Management, prepare a final "Technical Development Plan for a Discrete Address Beacon System."[2]
2. Carry out preliminary planning activities in preparation for undertaking the system engineering responsibility on DABS.
3. Initiate air traffic surveillance requirements studies (Task 1).

4. Initiate investigations of current system performance as a base for the trade-off studies of Task 2.

5. Continue field measurements of ATCRBS transponder performance.

6. Initiate investigation of critical areas related to the design of DABS.

Items 3 through 6 above are reported in greater detail in the following sections

II. SURVEILLANCE REQUIREMENTS ANALYSIS

As a first step in developing plans for improving air traffic surveillance and communications over the next 15 years, it is necessary to understand in detail the respective capabilities required to support the operational Air Traffic Control (ATC) system. These requirements are not unique since there are many ways of performing the ATC functions. In fact, ATC proceeded for many years without any means of traffic surveillance, and operates today with only partially implemented, rudimentary data-link capability (ATCRBS identity and altitude reporting). Thus, these requirements depend upon the objective and the structure of the ATC system.

In practice there is some interaction between studies of requirements and capabilities since requirements are not unique and capabilities can be provided in various ways, each way having a different cost.

Our studies have initially focused on surveillance requirements. Studies of communication requirements will be undertaken in future reporting periods.

A. Control of Approaches to Independent Parallel Runways

One of the functions which places particular demands on the surveillance system is the monitoring of independent IFR approaches to close-spaced parallel runways. The use of these runways spaced one-half mile apart was recommended by ATCAC in order to achieve more efficient utilization of existing airport real estate. Mathematical models[3,4] which evaluate the collision risk have been used to calculate the minimum acceptable spacing of runways. In these models, the uncertainty in aircraft position is represented by a normal distribution dependent upon the limited accuracy of the landing guidance system. These models represent the operating mode in which aircraft are making a normal descent through an approach corridor (normal operating zone) that extends a few hundred feet to either side of the runway centerline. Another operating mode which has been investigated[5-7] is that corresponding to an emergency situation where the aircraft for some reason has strayed off course and, after receiving a command from the controller, executes a recovery maneuver. The results presented by the various authors are quite different because they are extremely sensitive to the assumed worst-case blunder maneuver, the width of the normal operating zone, the controller-pilot-aircraft response time, and the surveillance system error.

In all the above references, false-alarm probabilities and detection probabilities were not calculated. Also, the assumptions made in deriving the model were not verified. Accurate estimates of aircraft cross-track position and velocity are needed to transmit an emergency command at the right time. This imposes stringent requirements on the range and azimuth estimation accuracy, data rate, low-angle coverage, and the tracking algorithm. The objective of our study is to utilize and expand on past work effectively in order to obtain a range of options for an approach monitoring system from which a cost-effective choice can be made. The following sections provide a breakdown of the problem and summarize our accomplishments thus far.

1. Basic Approach

This section outlines the various parts of the problem, many of which can be investigated in parallel. They include tracking, determining realistic assumptions to be made in modeling the situation, predicting the aircraft's future position, developing a decision algorithm, and choosing the best sensor.

Various filters for tracking maneuvering aircraft must be investigated. Five candidates that have been compared[8] under particular conditions are the Kalman filter, a simplified Kalman filter, an α-β filter, a Wiener filter, and a two-point extrapolation. Of these five candidates, the Kalman filter* is the most sophisticated, potentially the most accurate, but the most costly to implement. The final selection involves trade-offs between filter accuracies, filter implementation requirements, and system performance goals and limitations.

As mentioned earlier, various assumptions have a substantial effect on the calculation of a "safe" centerline spacing. One important assumption is the worst-case maneuver expected of all aircraft on final approach. This, coupled with the maximum speed of the aircraft and the turn rate, would give the maximum lateral distance needed for a recovery turn maneuver. Also closely related to the worst-case maneuver is the associated lateral distance traveled during the assumed controller-pilot-aircraft response time. An FAA simulation study at NAFEC found that such a response time has a mean of 6 seconds with a 1σ deviation of 2.4 seconds.[9]

In order to make decisions as to whether a command to maneuver should be given, predictions of the aircraft's position (and perhaps heading and velocity) should be made into the future for a time equal to the controller-pilot-aircraft response time plus the time for a corrective turn maneuver. The resultant errors in predicting cross-track position will have an important effect on the required centerline spacing. Conversely, the centerline spacing has a substantial effect on the prediction accuracy required.

The decision algorithm utilizes the tracking algorithm and the prediction calculations according to some chosen detection strategy. Certain thresholds which involve aircraft cross-track position, velocity, and acceleration are determined; if a threshold is exceeded, a command to turn is made. These thresholds are a function of the permitted false-alarm and detection probabilities and have a direct influence on the resultant centerline spacing.

Once the requirements on data accuracy, data rate, and airspace coverage are known, alternate approaches to obtaining good sensor data can be investigated. For instance, one approach may be to use down-linked microwave ILS data in conjunction with that obtained from a ground sensor (or sensors). In another approach, accurate cross-track data may be obtained from auxiliary receivers used in conjunction with a DABS or ATCRBS interrogator.

2. Primary Results

A Kalman filter tracking algorithm[8] was programmed on the computer. The sensor coordinates (r, θ) rather than Cartesian coordinates (x, y) were chosen for the filter mainly because the measurement noise covariance matrix is diagonal. The effects of maneuvers, irregular deviations from straight-line motion, and nonlinearities in the true equations of motion of the aircraft are represented by a noise which drives the linearized equations of motion. We denote this noise as maneuver noise. This filter was tested with a variety of realistic aircraft trajectories

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* This type of filter combines present and past measurement data in such a way that a quadratic error criterion is minimized assuming that the aircraft obeys a particular linear dynamic model.

approaching the turn-on point and along the extended centerline of a runway. Surveillance accuracies of 150 feet and 0.2° were assumed, and a nominal aircraft approach speed of 135 knots was chosen. By optimizing the tracker for each of the flight paths, the effective range of the variance of the maneuver noise was obtained. Work is now in progress in developing a tracking algorithm that will automatically adjust this variance according to changes in $\dot{r}$ and $\dot{\theta}$.

Projections of possible aircraft positions and velocities forward in time allowing time for system response and corrective turn maneuver were demonstrated by augmenting the Kalman filter. Conversion was first made to the Cartesian coordinate system since cross-track position and velocity are most important for parallel approach operation. The filter error covariance matrix[8] was projected ahead using the standard state transition matrix for straight-line motion. A new matrix was formulated for projections into the corrective turn. The resulting errors agreed very closely with the statistics of projected tracking errors using a Monte Carlo simulation technique. These predictions were made for aircraft trajectories intersecting the centerline at various angles.

B. Control of Lateral Deviations

Another important function is the monitoring and detection of lateral deviations from course by controlled aircraft flying along assigned airways. Previous work on determining safe separation between parallel airways[6] has included consideration of false-alarm probability and probability of detecting a deviation. The airway width, centerline spacing, and the required surveillance reliability, accuracy, and data rate will be determined in a way similar to that described for the parallel approach monitoring function.

C. Intermittent Positive Control

It is likely that, in terms of the amount of data processing required and the burden placed on the surveillance system capacity, Intermittent Positive Control (IPC) will be one of the most demanding ATC functions. This is due primarily to the large number of aircraft that will require IPC service and to the special nature of an automated decision-making system.

We have sought to identify the performance factors which might be used in the evaluation of various IPC design options. These factors include the level of safety, costs to user, rate of commands, data processing requirements, and pilot acceptability. The parameters of the surveillance system that are most significant in meeting IPC objectives are data content, data accuracy, data rate, sophistication of tracking algorithms, and command-link acceptability.

An attempt has been made to identify the major components of an IPC system and to consider the design options which exist for both hardware and software. It has been found that in many cases there are widely differing alternatives which must be examined as separate design candidates.

The extent to which the IPC system can take advantage of better surveillance data is strongly dependent on the content of the commands and the sophistication of the hazard evaluation software. We are currently examining three alternative hazard evaluation algorithms which differ from each other in computational complexity and command rate. One algorithm treats motion in each spatial coordinate separately; another proceeds in a state space based upon rectilinear motion; the third employs linearized equations of motion with a search for worst-case maneuvers. Of major interest is the manner in which the efficiency of these algorithms is affected by the necessity of being safety-conservative in the presence of tracking errors. Any algorithm can be made conservative merely by increasing the warning times, separation requirements, or acceleration limits, but a more desirable approach is to explicitly include tracking error estimates in the evaluation process.

D. Other ATC Functions

The surveillance and data communication requirements necessary to support other ATC functions must be determined. These ATC functions include control of vertical (altitude) deviations and perhaps longitudinal deviations from desired values as well as the generation of special flight instructions. These instructions may be in the form of vectors or other commands and may originate from a human controller, a metering and spacing system in the terminal area, or a flow control or metering system in the en route area. These instructions may arise from the need for controlled aircraft to be at a certain place at a certain time or from the need to avoid passing too close to another aircraft. The surveillance and communication requirements presented by these ATC functions are likely to be different in different portions of the airspace. Work on determining these requirements is in the formative stages.

III. ATCRBS CAPABILITY

Another important step in developing the strategy for improving the surveillance and communication systems is the development of an understanding of the capability of the present system, improvements to the present system, and proposed new systems. The initial focus of our effort has been on developing a detailed understanding of the present system. During future reporting periods, studies will focus on determining the capability of specific alternative approaches to meeting ATC surveillance and communication requirements. These approaches will include evolutionary improvements to ATCRBS, with and without changes in aircraft equipment and with and without improvements to primary radar. More far-reaching improvements including monopulse, controlled interrogation and sensor-data netting will be examined. Approaches employing DABS and VHF data link will also be examined.

A. Signal Processing

The target-detection and azimuth-estimation performance of the ATCRBS portion of the NAS Stage A Common Digitizer has been analyzed. Both target detection and azimuth estimation were investigated for the cases where the input signal to the common digitizer (1) had not been preprocessed by a defruiter, (2) was first passed through a standard signal correlation defruiter, and (3) was first passed through a double correlation defruiter as in military GPA-122 coder/decoder group (double correlation defruiting is not the same technique as FAA double defruiting).

Previous work dealt only with those cases where the beacon transponder reply run length was equal to the processor window length. This work has been expanded to include cases where the run length exceeds the window length. (Such a situation exists for NAS where the nominal run length is 45 with a 1:2 or 1:3 mode interlace pattern for a processor window size of eleven.)

Initial results show that the double correlation defruiter gives slightly higher target-detection probabilities and improved azimuth estimation while maintaining an equal or lower probability of false alarm.

A probabilistic state approach to the problem of determining detection, false alarm, and azimuth-estimation performance has also been investigated. The approach is particularly appealing for problems involving unusually long run lengths. Examples of possible applications for the method are:

(1) Azimuth estimation in the presence of fruit,

(2) Resolution of two closely spaced targets (in azimuth),

(3) False-alarm probability distribution per scan.

The digital processing in the current ATCRBS is typically analyzed on the basis of binary random variables – a one representing a hit, a zero representing a miss. The usual assumption is that successive replies are statistically independent and identically distributed. The validity of these assumptions is subject to question; hence, more realistic models have been investigated. When the replies originate from a legitimate target, the possibility of a miss increases with transponder dead-time and with channel occupancy. Simple analytic expressions have been found which relate probability of miss to dead-time and channel occupancy.

B. Transponder Test Program

In view of the growing volume of air traffic and the capacity limits of the present ATCRBS, it was deemed advisable to make field measurements of existing transponders to gather data that could be used both in evaluating the present system operation and in planning future developments.

The program was undertaken to provide a measure of the primary characteristics of the transponders in a random sample of general aviation aircraft. It was planned to indicate in general terms the degree to which operational general aviation transponders meet the current Minimum Operational Characteristics. The test program is not intended as either a comprehensive evaluation of all transponder characteristics or a competitive evaluation of units of different manufacture.

As a compromise between the most realistic measurements possible, which would involve a highly instrumented and extensive flight test program, and the desire to minimize cost and time duration, it was decided to conduct the tests on the ground with the aircraft engine running and with other radio/navigation equipment turned on. This decision set constraints on the time that could reasonably be allocated to measurements. A target time of 10 to 15 minutes for the active test of an aircraft was established.

The tests were performed with the aircraft parked on a suitable run-up pad and the mobile test van parked nearby. Coupling to the antenna of the aircraft under test was accomplished through the use of a horn antenna as illustrated in Fig. 1.

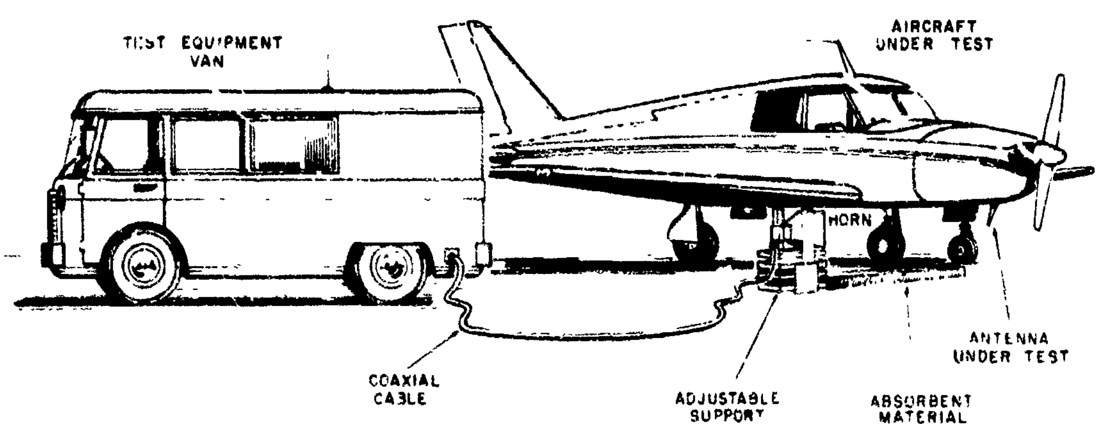

Fig. 1. Typical test setup.

The following transponder characteristics were measured:

- Frequency
- Dead-time
- Suppression time
- Delay
- Squitter
- Sensitivity
- Power output

The initial phase of the program, supported by an earlier Interagency Agreement, was begun on 24 May 1971, and the field testing was completed on 12 July 1971. Following the field test, which included measurements on 96 aircraft, a data reduction and report preparation effort commenced. The report effort was completed with the publication of an interim report.[10] Following an informal reporting of the results of the first phase tests, the Laboratory was asked to extend the program to cover the testing of approximately 500 aircraft.

The field test is continuing. Approximately 250 aircraft have now been tested. The results being obtained are consistent with the data gathered during the first phase of the program as summarized in the interim report.

Detailed discussions of the first-phase results are given in the Interim Report. A brief summary follows.

Frequency:– Approximately 6 percent of the operable transponders tested were out of the frequency specification limits.

Dead-Time:– A tight bunching of dead-time around 35 μsec was found. Five of the first 96 units tested had very long dead-times which were far out of specification.

Suppression Time:– Suppression times were found to be rather evenly distributed over the specification range from 25 to 45 μsec.

Delay:– Transponder delays were generally found to be within the specification limits of 2.5 to 3.5 μsec.

Squitter:– Squitter was not found to be a significant problem with the transponders tested.

Sensitivity:– A rather uniform distribution of sensitivity readings was found over the region from −65 to −80 dBm.

Power Output:– Power outputs were generally distributed between 18 and 28 dBW.

IV. CRITICAL DABS DEVELOPMENT AREAS

During the present reporting period, the Technical Development Plan for DABS was completed. Planning for our role as System Engineering Contractor for DABS has commenced. Investigations of a number of the critical problem areas in the DABS development have begun during the present period.

A. DABS Interrogation Scheduling

In order to realize the freedom from synchronous garble inherent in the DABS concept, it is necessary to devise algorithms for the scheduling of DABS interrogations. A useful algorithm must accept a target list, which will contain target identity, time of last position update, last reported position, and track data in some form, on each target, and it must prepare an interrogation schedule which will make efficient use of the channel without permitting replies to overlap. The schedule will operate in advance of the real time period being scheduled, and will also schedule ATCRBS interrogations according to a pre-assigned DABS/ATCRBS interlace scheme. Moreover, the DABS interrogations must satisfy the demands of both the surveillance and digital data-link communication functions.

The specific problem presented by interrogation scheduling is unique to the DABS system concept. It is also central to the DABS system design, and it interacts strongly with nearly all the other major DABS subsystems: antenna configuration, azimuth measuring technique, modulation/coding scheme used on the channel, interference environment, target tracking procedure, and all aspects of automated air traffic control and communications. In order to perform intelligent trade-off analysis between the interrogation scheduling subsystem design and the design of the other subsystems listed above, it is necessary to have a variety of practical algorithms available and a clear understanding of the costs (in complexity) and performance (in target-handling capacity) of each of them. Since the subject is new, it is important to make an early start in developing this area so that the requirements and difficulties connected with this phase of the DABS design may be factored into the over-all system design effort from the beginning.

As a start in this direction, a report[11] is in preparation which deals with the interrogation scheduling problem in general and with a number of algorithms in particular. The material is an outgrowth of work done in connection with the preparation of the DABS Technical Development Plan, supplemented by a more recent and continuing effort toward the development and evaluation of specific scheduling algorithms.

The report ontains a general description of the DABS system concept and a comprehensive discussion o scheduling problem and its relation to other aspects of the DABS design. The problem of time sharing an interrogator between an ATCRBS and a DABS mode is discussed in detail, and a general relation is derived which can serve as the starting point in the design of the DABS/ATCRBS interlace procedure. A number of algorithms are introduced and discussed in the context of an agile-beam phased array, with emphasis on the complications introduced by (1) monopulse, (2) a requirement for variable data rate and/or rapid-access communication, (3) an interrogation schedule interrupt capability (for emergency message delivery), and (4) the need to interlace ATCRBS and DABS interrogation schedules. A separate chapter is devoted to the rotating mechanical antenna and the constraints that it imposes on both scheduling and the resultant target-handling capacity. Finally, a brief discussion is included on the effects of target motion on scheduling and the corresponding tracking requirements to support the interrogation scheduling function.

B. Interference Model Development

Work has begun on developing models to represent ATCRBS up-link and down-link channel loading. These models will be used to assess quantitatively ATCRBS self-interference effects and ATCRBS interference effects on DABS designs operating on 1030 and/or 1090 MHz. Emphasis has been placed on models that can be scaled with interrogation population and transponder population in order to ultimately use these models to project the ATCRBS channel loading throughout the ATCRBS to DABS transition period. To coordinate work in this area, several discussions were held with representatives of the Department of Transportation/Transportation Systems Center, the Electromagnetic Compatibility Analysis Center, and the MITRE Corporation.

C. DABS Modulation and Coding Design

Early work in this area is oriented toward analysis of performance of candidate binary modulation systems in the presence of white noise, interfering signals (ATCRBS-like as well as DABS-like), and multipath garble. The investigations will include a variety of optimal and non-optimal signal processing techniques suitable for implementation in low-cost transponders as well as ground equipment.

D. Monopulse Analysis

Analysis of the accuracy of monopulse azimuth angle estimation techniques in the presence of white noise, multipath, and interfering signals has begun. Early efforts are oriented toward definition of experiments to model the various sources of monopulse errors.

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